Dark matter, electrons and anti-protons

Peter Fisher

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RAPID COMMUNICATIONS

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Search for "subthreshold" production of antiprotons and creation of fractional charges and new particles in relativistic nuclear collisions

S. Abachi,[a,*] A. Shor,[a,b,†] E. Barasch,[c] J. Carroll,[a] P. Fisher,[b‡] K. Ganezer,[a,§] G. Igo,[a] T. Mulera,[b] V. Perez-Mendez,[b] and S. Trentalange[a]

[a] *University of California, Los Angeles, California 90024*

[b] *Lawrence Berkeley Laboratory, Berkeley, California 94720*

[c] *University of California, Davis, California 95616*

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A search for "subthreshold" production of antiprotons and creation of fractional charges and new particles at 0° in the reaction $^{28}Si+^{28}Si$ at 2.1 GeV/nucleon has been made at six secondary rigidities. Except for one $\bar{p}$ candidate, no evidence for such production is found. A summary of upper limits on the yields for charges $-\frac{1}{3}$, $-\frac{2}{3}$, -1, $-\frac{4}{3}$, and -2 is presented. The results from all six rigidities are combined to yield upper limits of less than 1 particle per 10^4 to 10^7 collisions for the mass range $0.1 < M < 5.0$ GeV, and less than one $\bar{p}$ per 3.8×10^7 collisions.

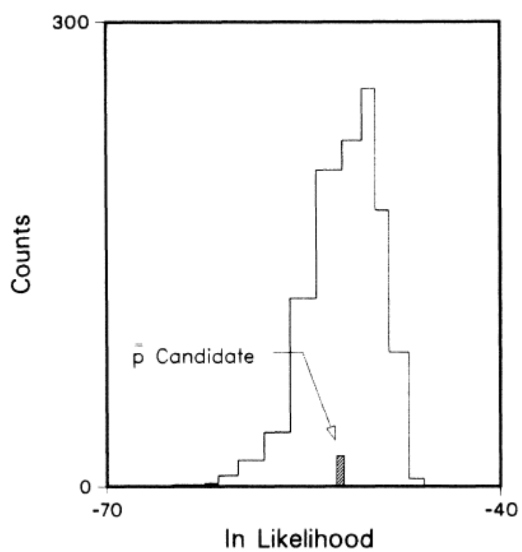
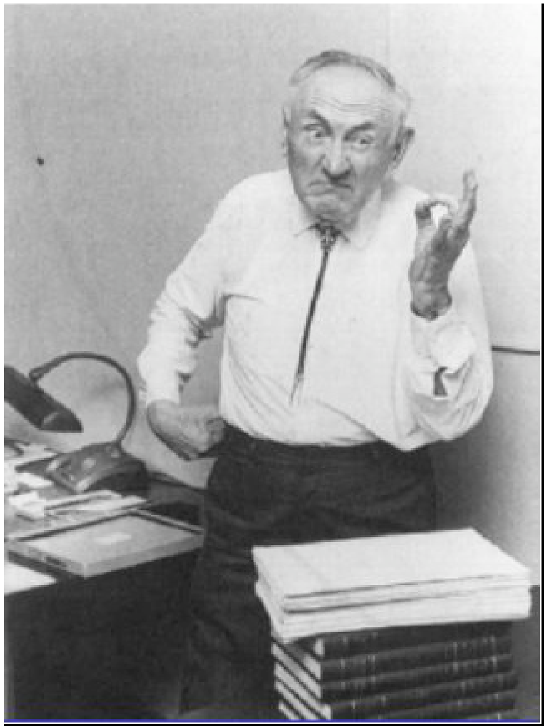


FIG. 2. Likelihood of the antiproton candidate at 1.42-GeV/c momentum, compared to the likelihood distribution of the observed protons.

Maybe one of the last antiprotons observed at the Bevatron

Outline

- The electron, positron, antiproton’s roles in the search for dark matter
- AMS-01- a first try
- A search for dark matter
- The AMS-02 - a bridge too far?



Origins of Dark Matter

Fritz Zwicky (1933) applied Virial Theorem to motions of "nebulea" (galaxies) in the Coma cluster and showed the motion implied gravitational potential far in excess of the amount of matter measured based on the light output of the nebulea.

$$G(t) = \sum_i \vec{p}_i \bullet \vec{r}_i$$

$$\left\langle \frac{dG(t)}{dt} \right\rangle = 0 = 2\langle T \rangle + \langle V \rangle$$

$$M_{Coma} > \frac{3}{5}\frac{R\bar{\bar{v}}^2}{G}$$

$$\left.\begin{array}{l} M_{galaxy} \sim \dfrac{M_{Coma}}{1000} = 4.5 \times 10^{10} M_{Sun} \\ L \sim 8.5 \times 10^{7} L_S \end{array}\right\} \rightarrow \gamma = 500$$

R~600 kpc, characteristic radius

$v^2 = 5 \times 10^{15} cm^2/s$, time & space averaged velocity

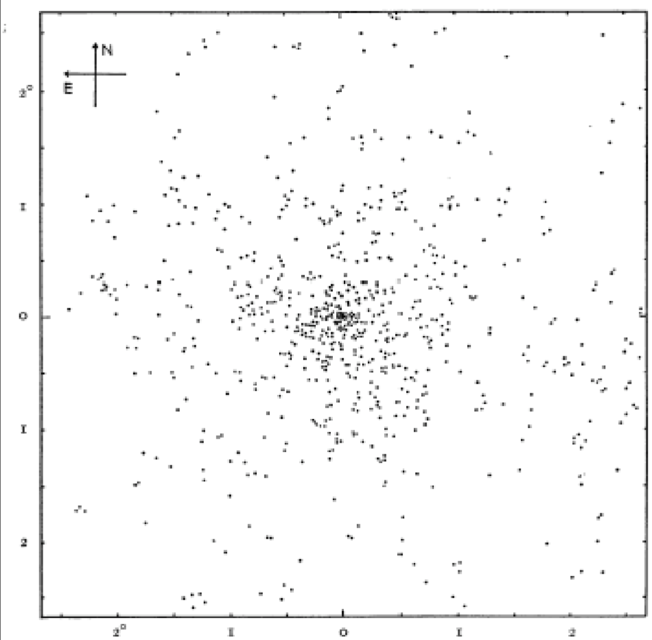
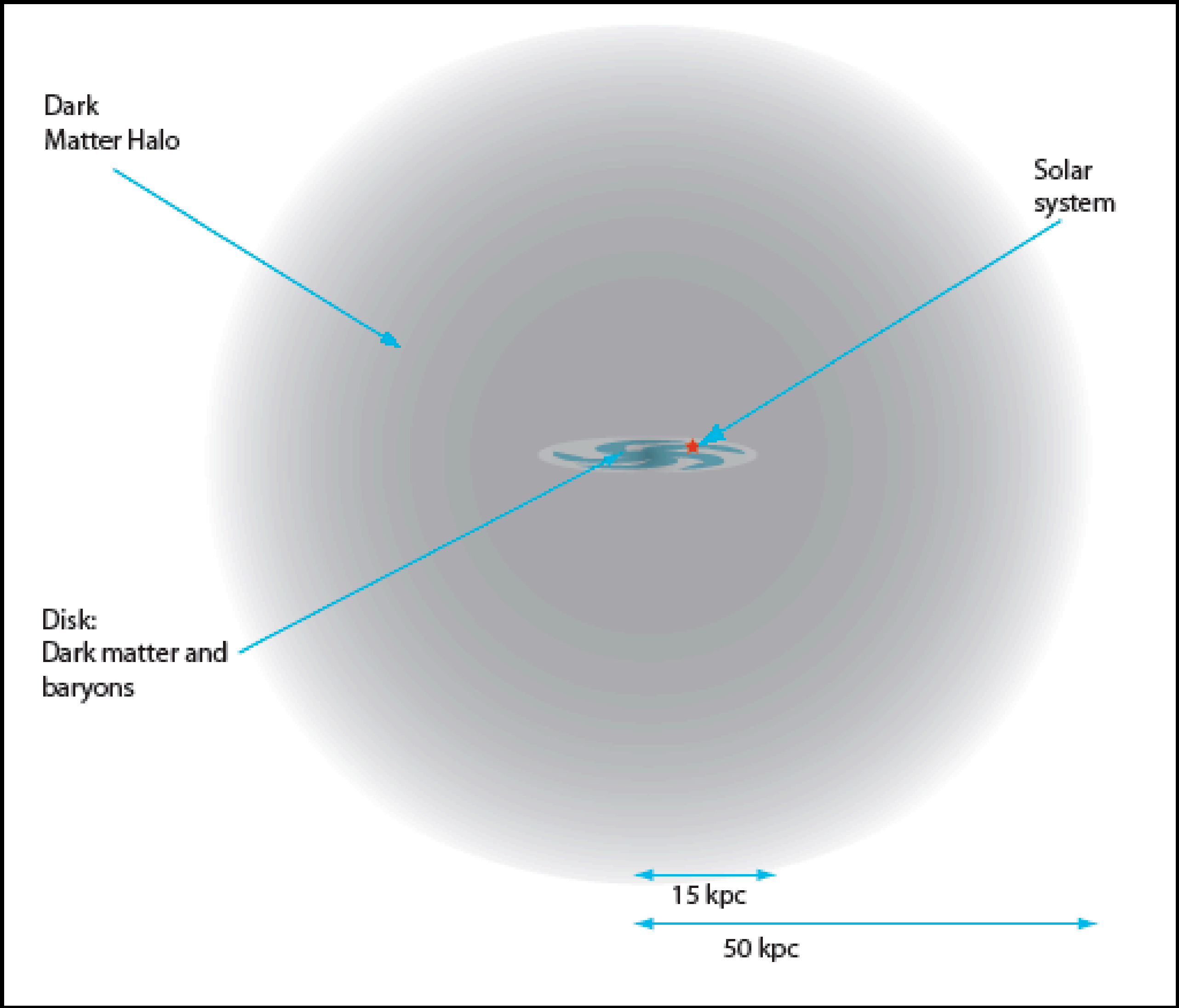


Fig. 3.—The Coma cluster of nebulae



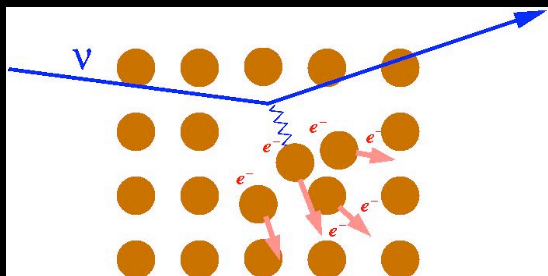
Contemporary picture:

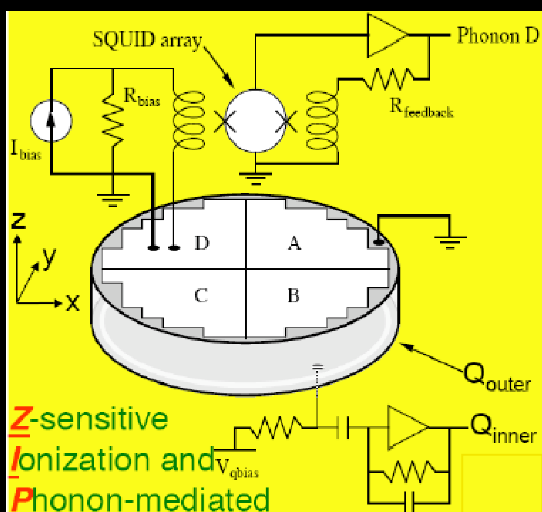
Halo surrounding baryonic disk

- May be large variations of DM density
- May be bulk motion of DM in halo
- May be satellite halos

Three methods of looking for evidence of dark matter

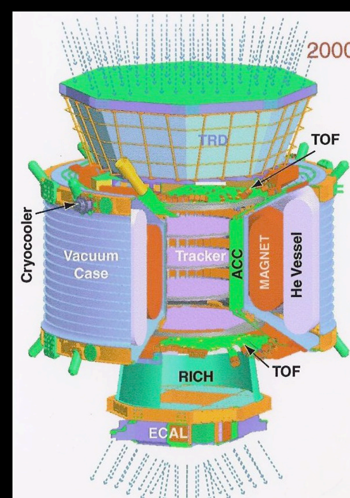
Nuclear recoil





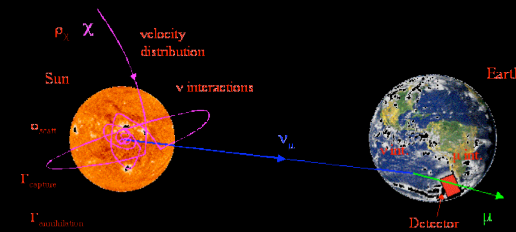
Recoiling nucleus with ~10 keV in matter

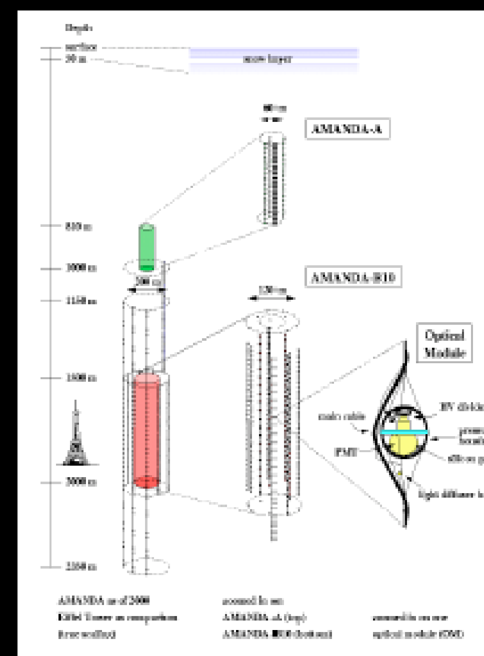
Annihilation in our galaxy



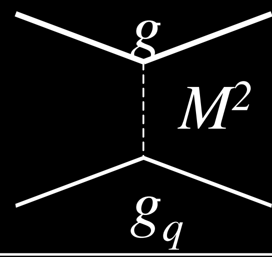
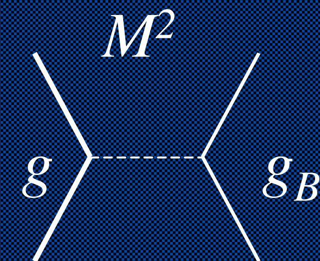
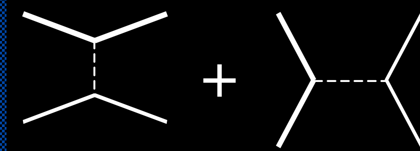
Excess electrons, positrons , gammas or antiprotons in cosmic rays

Capture followed by annihilation





Neutrinos from the Earth, Sun or galactic center

	Scattering	Annihilation	Capture and Annihilation
Process			
Density	n	n^2	n^2
Rate	$g^2 g^2_q/M^4$	$g^2 g^2_B/M^4$	$(g^2 g^2_q/M^4)(g^2 g^2_B/M^4)$
Majorana/Dirac suppression	Majorana suppressed by N^2	Majorana not suppressed	Partial suppression for Majorana
Sampling	Flux at Earth now	Flux in local 3kpc now	Flux integrated over lifetime of galaxy
Experiments	CDMS CRESST ZEPLIN	AMS, HEAT,GLAST, CAPRICE, PAMELA	SuperK AMANDA ICECube

Three methods of looking for evidence of dark matter

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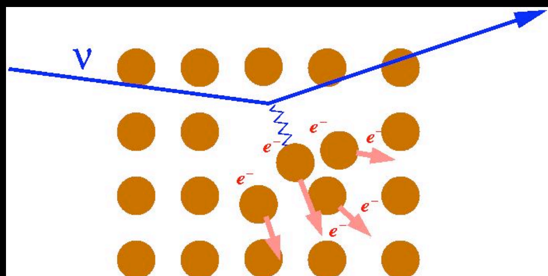

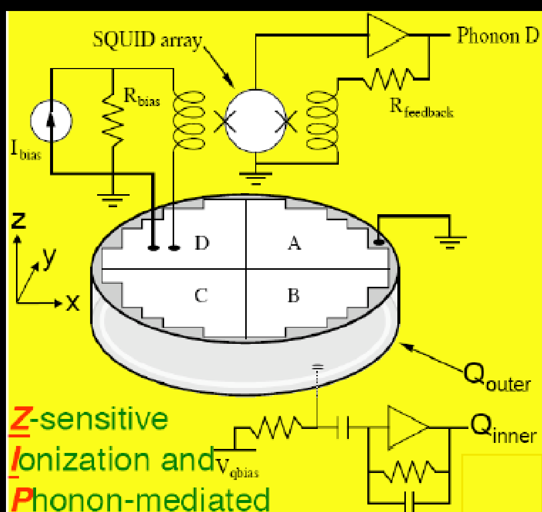

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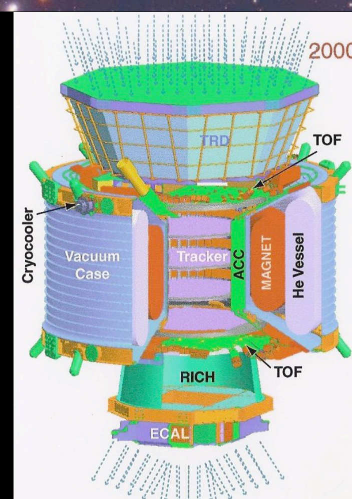
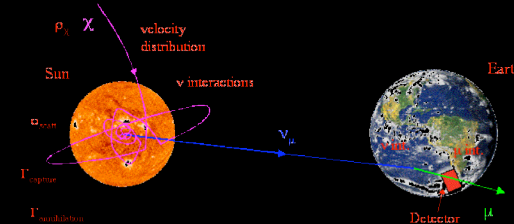
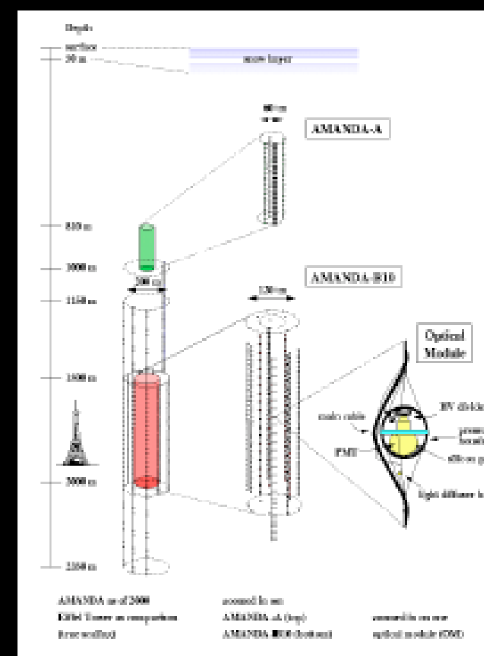


Excess electrons, positrons , gammas or antiprotons in cosmic rays

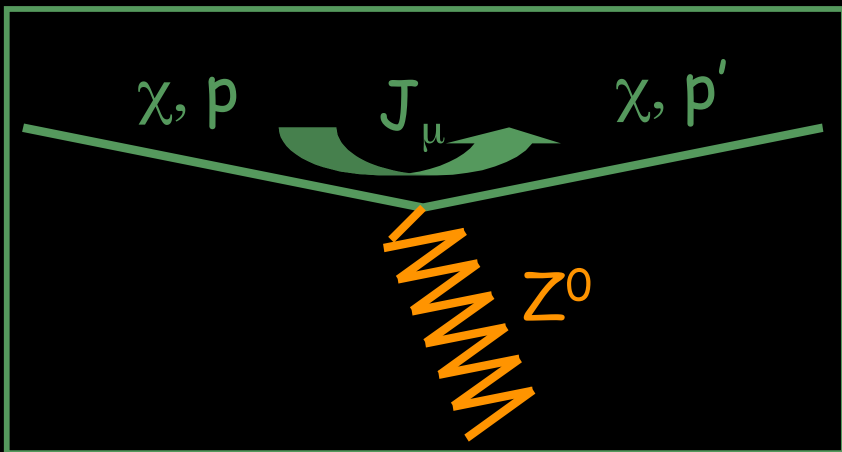
Capture followed by annihilation





Neutrinos from the Earth, Sun or galactic center

DM neutral current interactions



Neutral current:

$J_\mu = \psi(p')(C_V\gamma_\mu - C_A\gamma_\mu\gamma_5)\psi(p)$

Vector

Axial-vector

$\boxed{p \rightarrow 0}$

$J_0 = C_V\psi(p')\psi(p)$

Dirac, scalar

$$\frac{d\sigma}{dT_R} = \frac{G_F^2 M c^2}{8\pi v^2} N^2 \exp\left(-\frac{M T_R R^2}{3\hbar^2}\right)$$

$\vec{J} = C_A\psi(p')\,\vec{S}\,\psi(p)$

Dirac,
Scalar
Majorana

$$\frac{d\sigma}{dT_R} = \frac{2G_F^2}{\pi\hbar^2 T_R^{\max}} \mu^2 \lambda^2 J(J+1) \sum_q T_q^3 \Delta q$$

Nuclear physics

Nuclear spin

Quark content

DM neutral current interactions

Dirac (Spin Independent, SI)

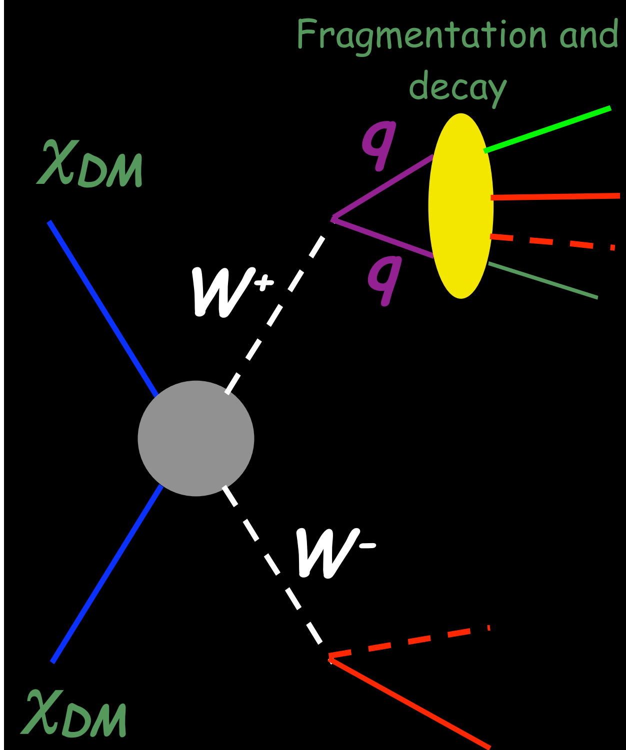
- Elastic cross section proportional to N^2 (~1600 for Ge)
- Independent of nuclear spin
- Simple nuclear physics

Majorana (Spin Dependent, SD)

- No enhancement from coherence
- Proportional to J(J+1)
- Complicated nuclear physics, QCD

If a recoil signal is observed, do not know if it is from SI or SD, $s_{SI} \sim N^2 s_{SD}$

The annihilation channel is more complex (depends on neutral scalars) and Majorana is not obviously suppressed relative to Dirac.

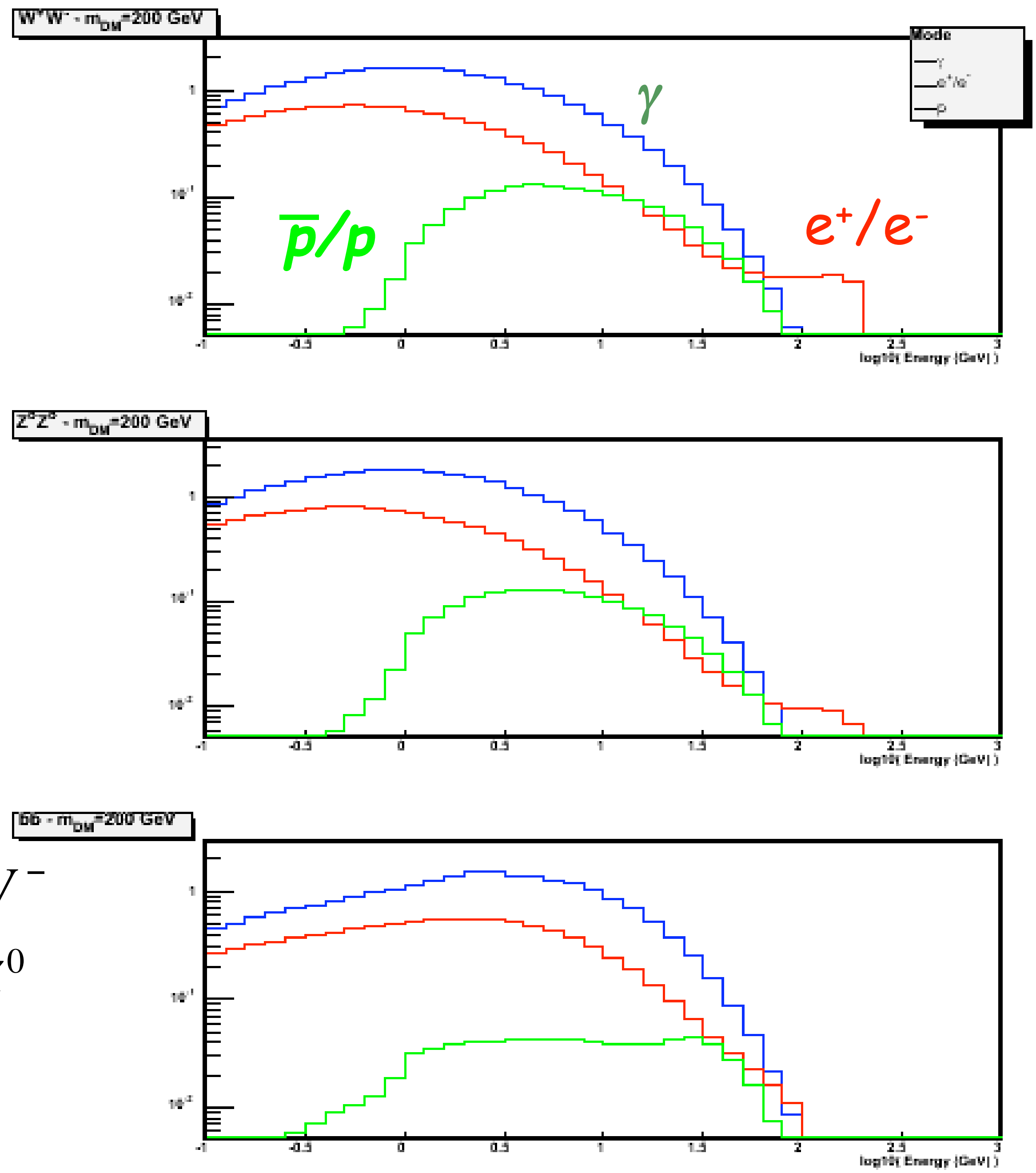


Typical processes:

$$\nu_{DM} + \nu_{DM} \rightarrow W^{+} + W^{-}$$

$$\nu_{DM} + \nu_{DM} \rightarrow Z^{0} + Z^{0}$$

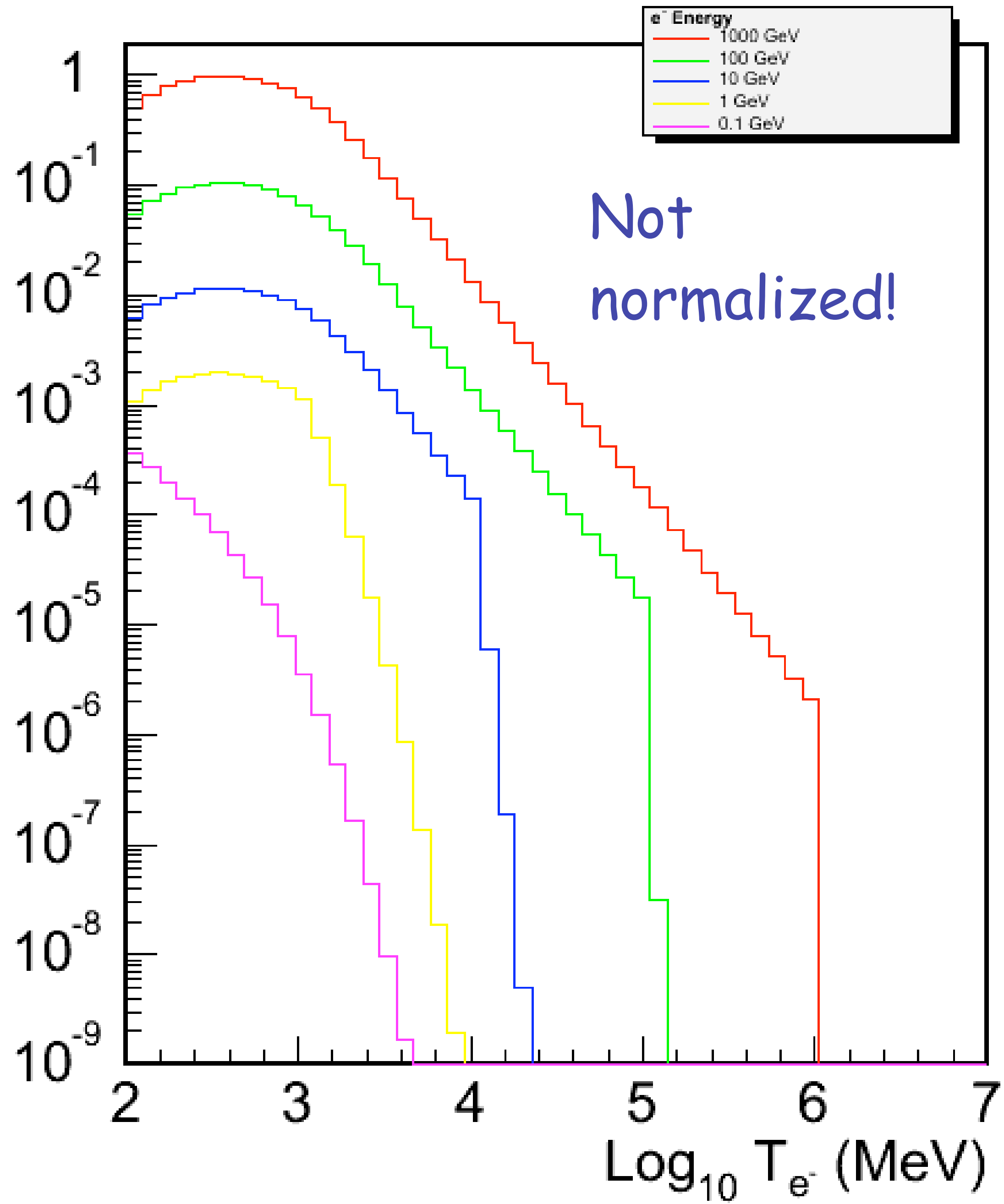
$$\nu_{DM} + \nu_{DM} \rightarrow b + \bar{b}$$

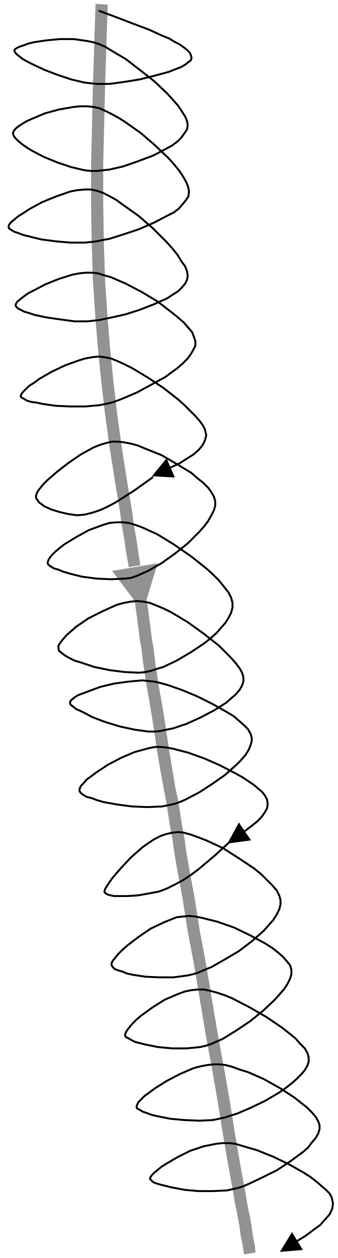


Propagation

Galprop - I. Moskolenko and A. Strong - cosmic ray propagation problem fit to all CR known data

Green's functions - expected flux on Earth for uniform monoenergetic source of electrons

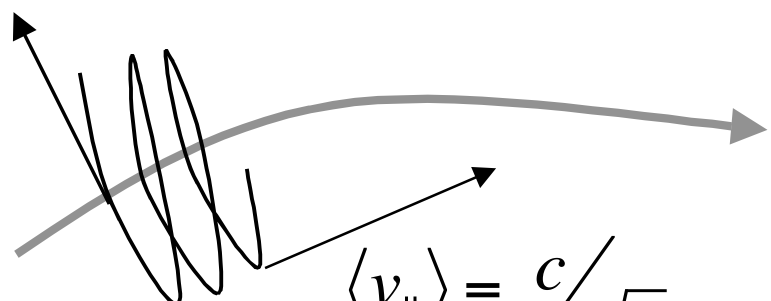




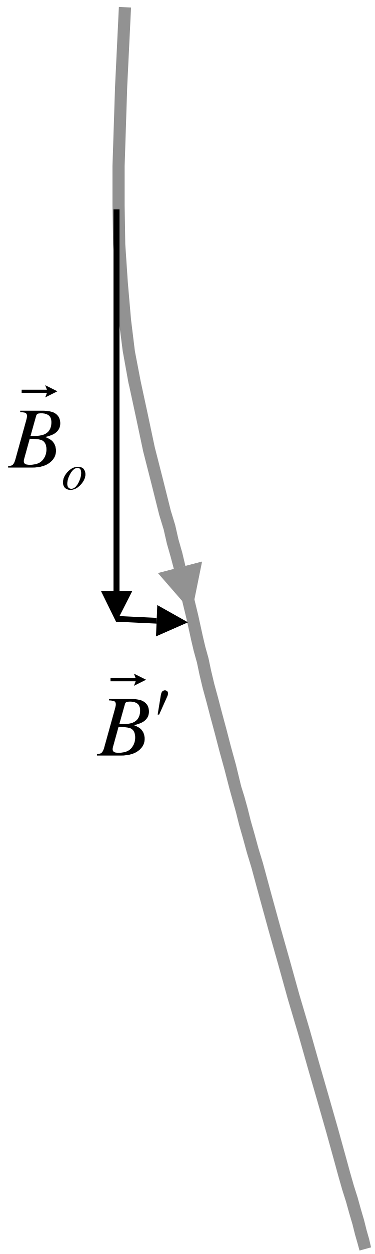
Charged particles follow magnetic field lines

$$r_L = \frac{p}{0.3\,\frac{\text{GeV}}{\text{T}-\text{m}}\,B} \approx 7\,\text{AU}$$

$$v = c$$



$$\langle v_{\parallel} \rangle = c/\sqrt{3}$$

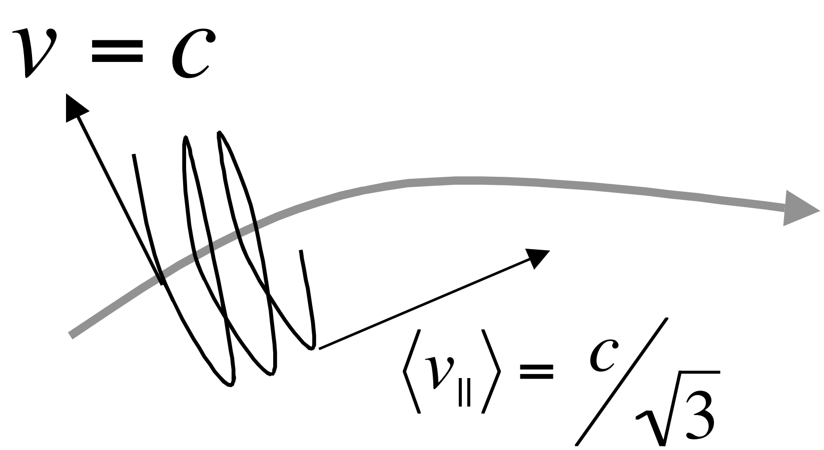


Magnetic turbulence - average variation of magnetic field:

$$\eta = \frac{\left\langle \vec{B}' \right\rangle}{\left\langle \vec{B}_o + \vec{B}' \right\rangle} \approx 10^{-4}$$

Mean time between scattering from inhomogenieties:

$$\tau_s = \frac{1}{\eta \omega_L} \approx 10\mathrm{y}$$



30 GeV electron: v=c, gives average velocity along field $c/3^{1/2}$

Electron lifetime determined by time τ_o to propagate one X_o=65 g/cm^2 in hydrogen

For a proton, the relevant scale is λ_N=51g/cm^2

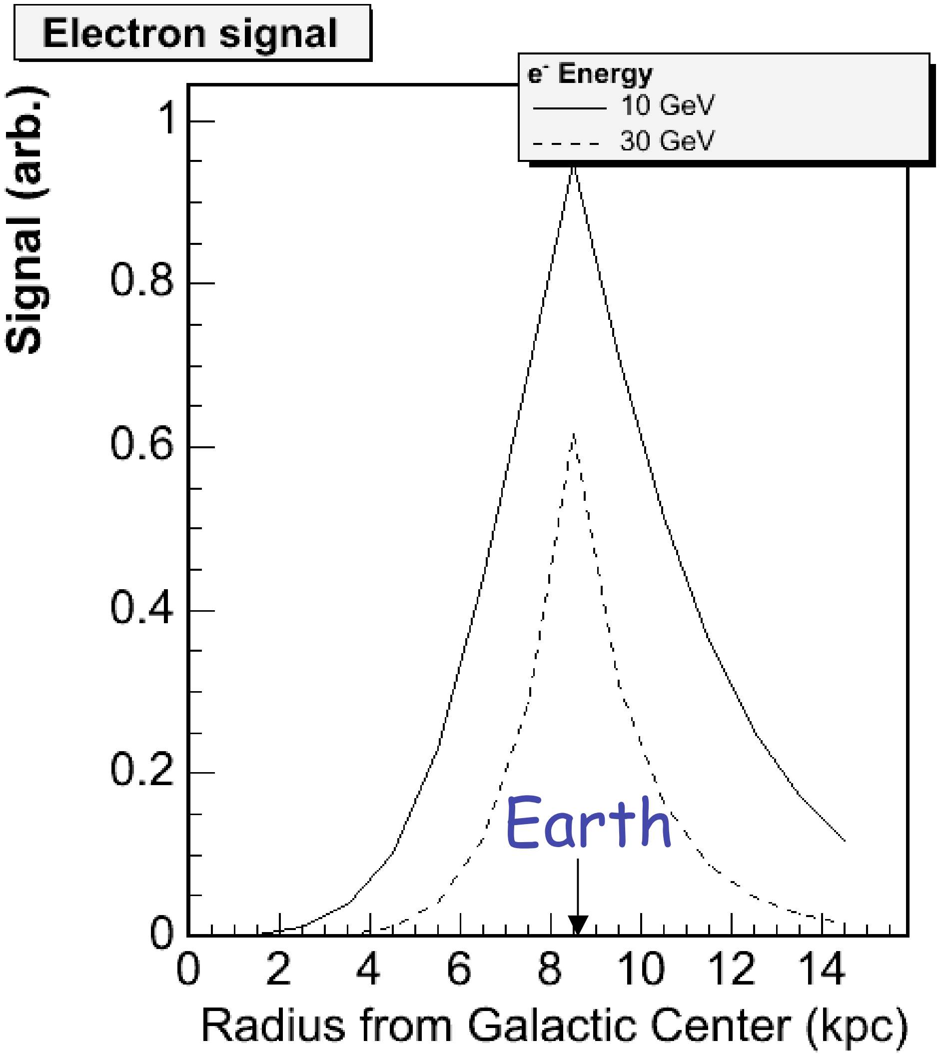
1 proton/cm^3 in ISM $\Longrightarrow$ X_o=1.3 x 10^{13} kpc

$\Longrightarrow$ τ_o=45 My

Number of scatterings: $N=\tau_o/\tau_s$

Random walk diffusion distance

$$d = \underbrace{\langle v_{\parallel} \rangle \tau_s}_{\text{Advance each step}} \underbrace{\sqrt{N}}_{\text{RMS number of steps}} = \sqrt{\underbrace{\frac{1}{3} c^2 \tau_s}_{\text{Diffusion coefficient}} \tau_o} \approx 3\text{kpc}$$

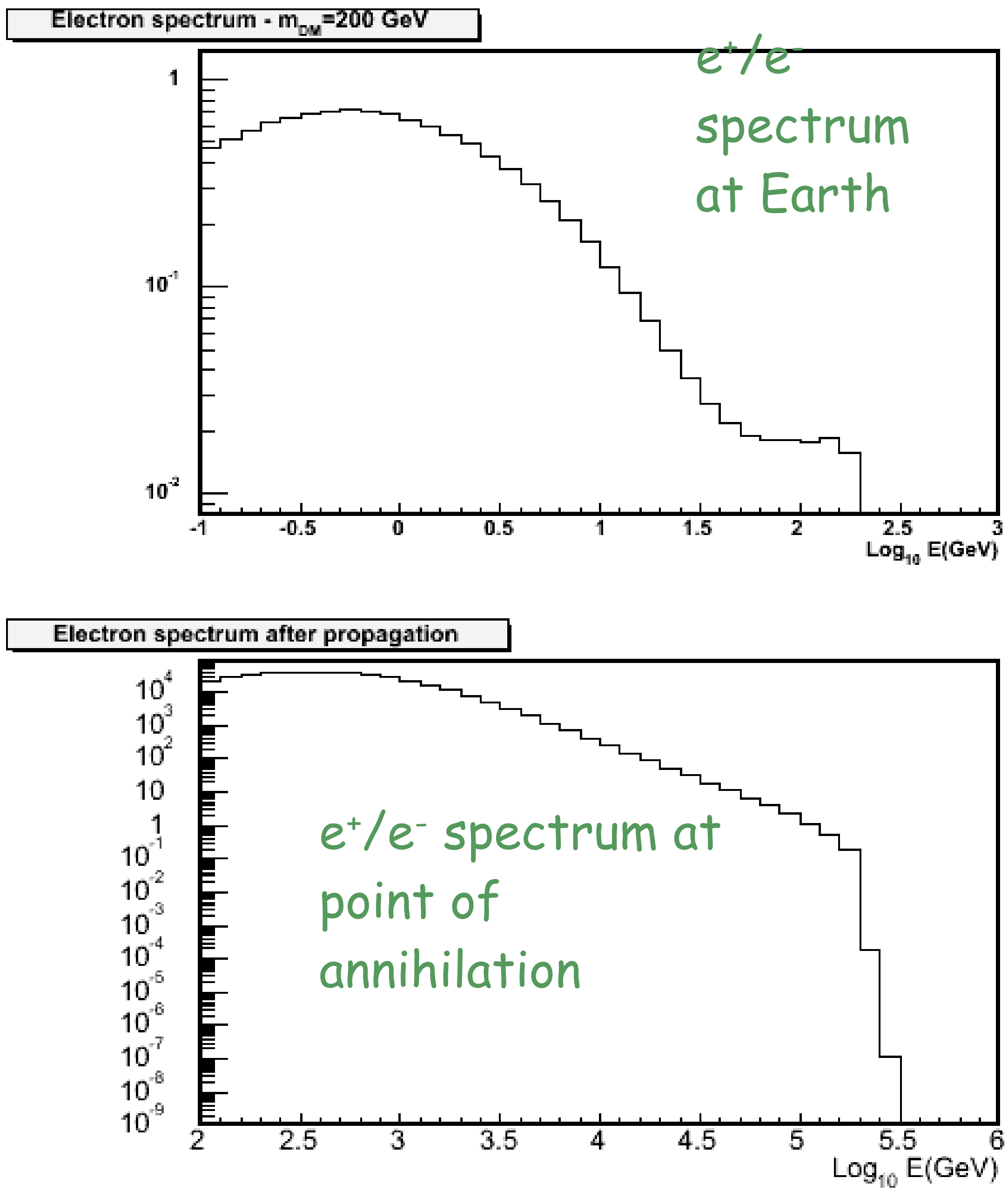


Integrated positron signal above 8 GeV for 100 GeV (solid line) and 30 GeV (dotted line). The Earth is located at 8.5 kpc radius.

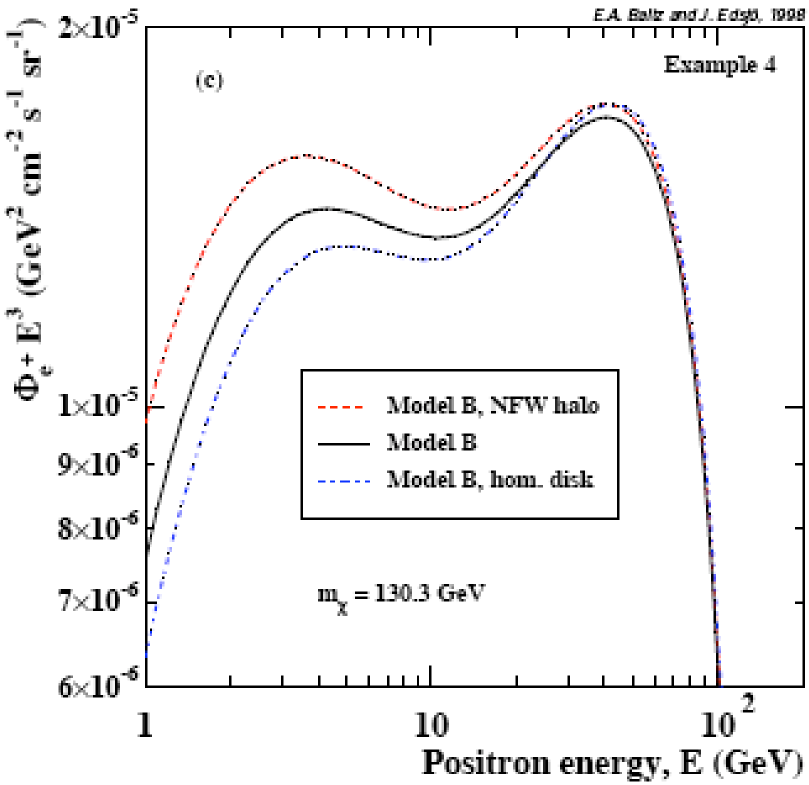
Contribution of DM outside of plane of galaxy difficult to understand - magnetic field structure not well known

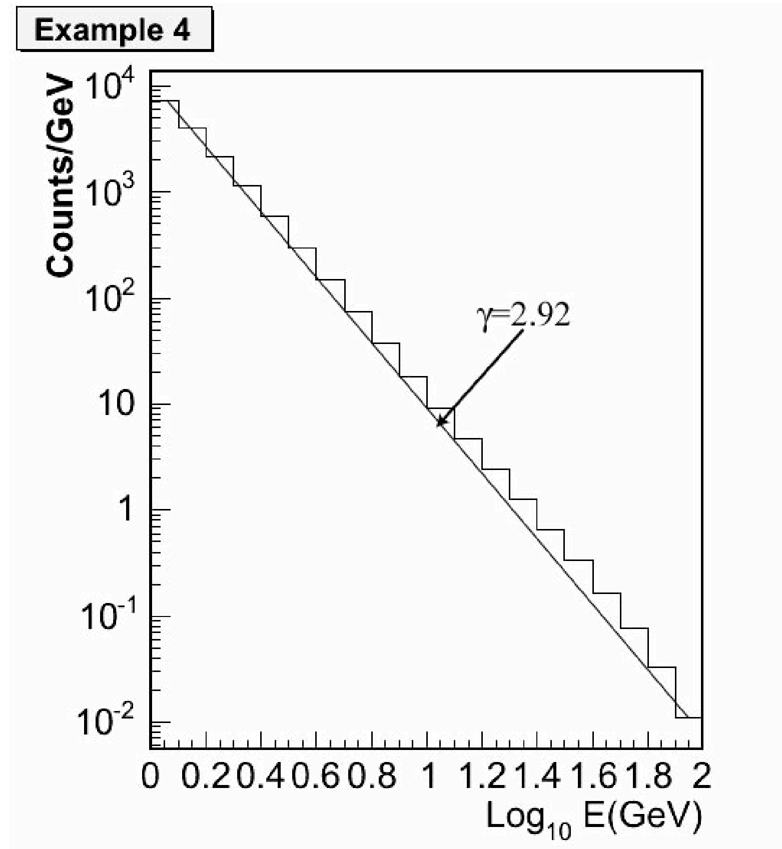
Propagation makes a mess!

During 3 kpc transit, DM annihilation products go through ~1 X_o or 1 λ_N of material



“Typical” signal - neutralino annihilation





Moral - in cosmic rays everything looks like

$$\frac{dN}{dE} \propto E^{-(2.5 \text{ to } 3.2)}$$

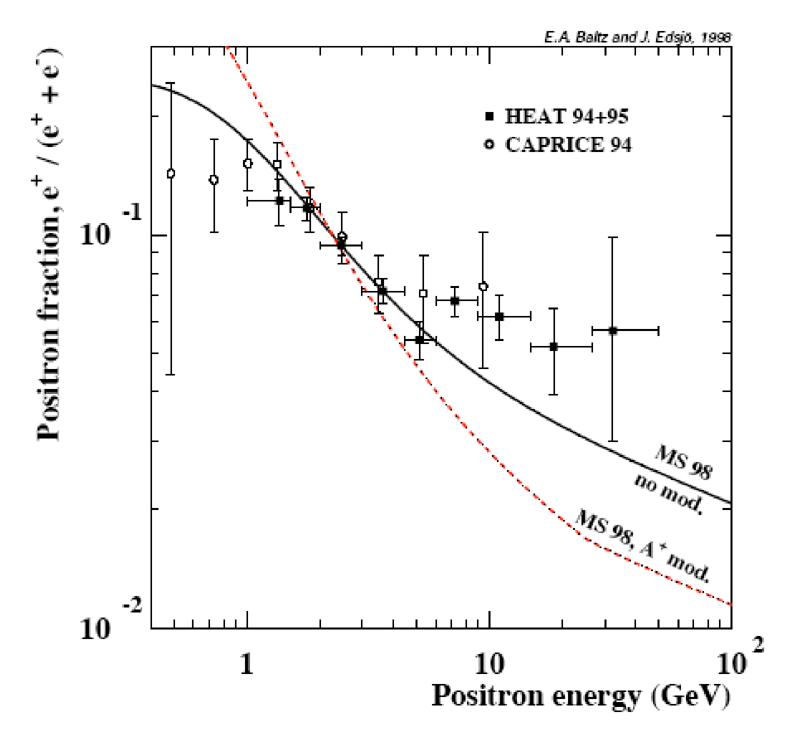
For a search for dark matter annihilation products, one should measure the spectra of

- Electrons - sharp cutoff from prompt decays in some models
- Positrons - low background rate, high signal rate, sharp cutoff from prompt decays in some models
- Antiprotons - low background rate, moderate signal rate
- Photons - directionality, but possibly large backgrounds

Ideally, one would have a single detector for all four and then carry out a simultaneous fit to a series of models.

HEAT and AMS-01 have begun with electrons and positrons.

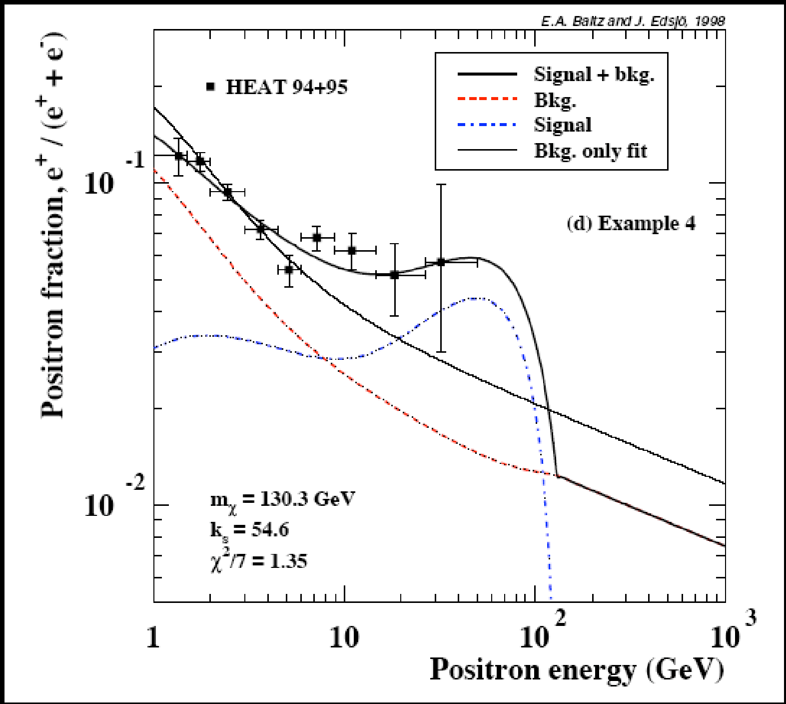
There are interesting results from HEAT…

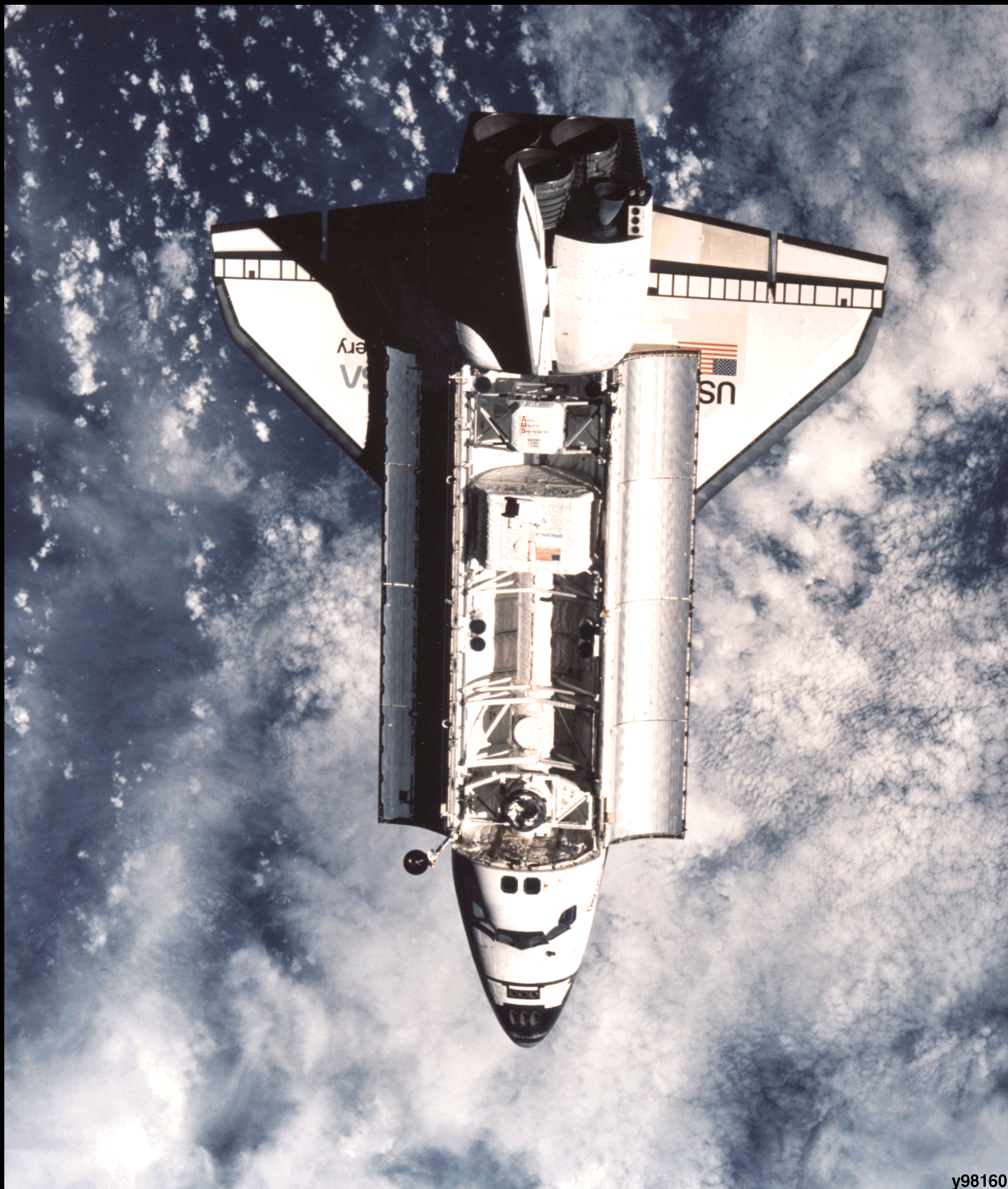


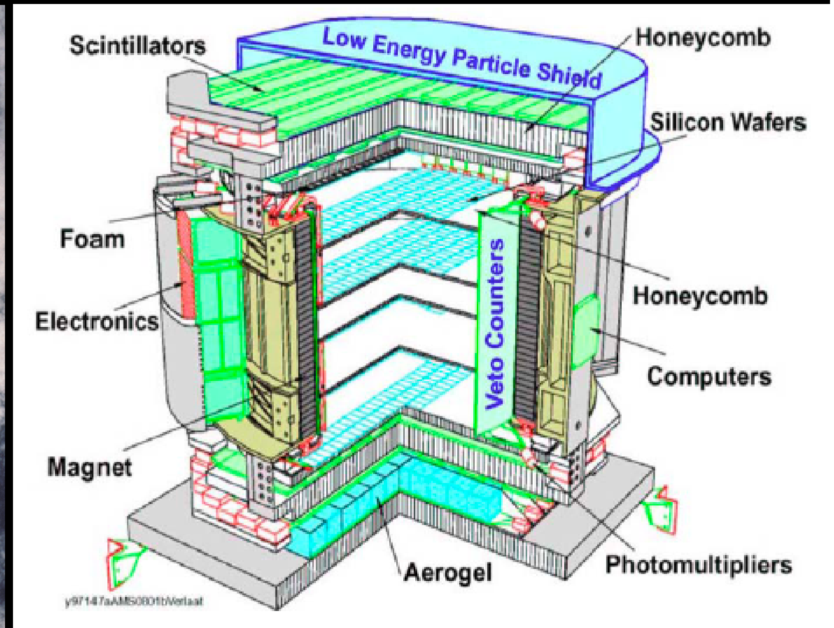
This first problem is that the propagation (especially solar modulation) is not well understood…

…the second is that HEAT runs out of sensitivity at ~50 GeV…

Fit with expected (smooth) normalization with signal (bump) gives 55 times higher relic density than observed



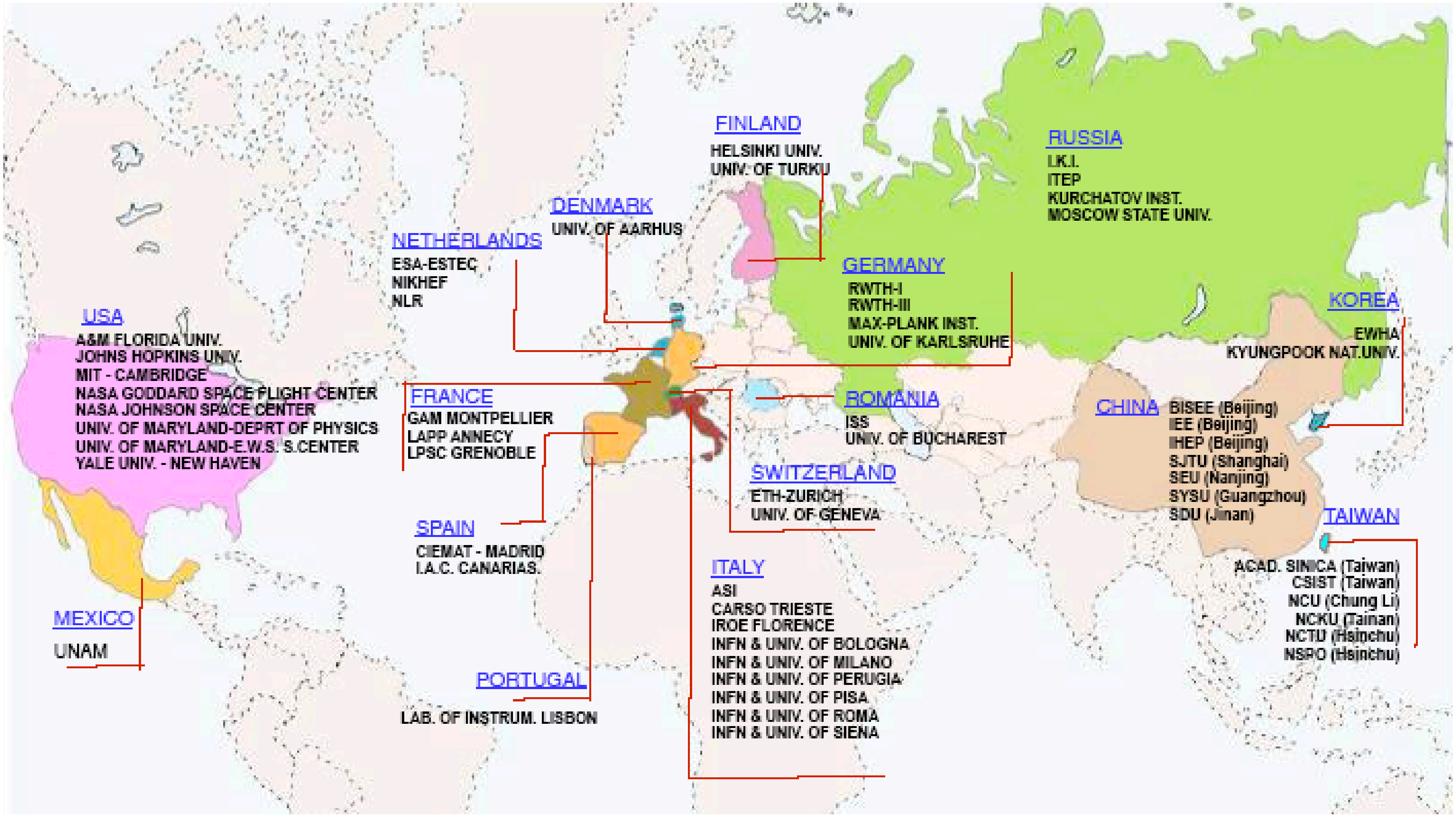




AMS-01 - June 1998

- ~100 h data taking at 400 km
- 200 M triggers
- 6 plane silicon tracker in 1500 G field
- 4 plane TOF system
- Aerogel thershold Cerenkov counter (~5 GeV)

AMS Collaboration



AMS-01 had no particle ID above a few GeV, so

- Select clean Z=-1 events
- Compute all Z=-1 backgrounds from expected CR source
- Use PYTHIA to compute signal spectra for electrons and anitprotons from W, Z and b decays at center of mass energies from 100-1000 GeV (Note: we do not yet consider SUSY models; our limits will be applicable for any process which has ZZ, WW or bb final states.
- GALPROP finds signal spectra at Earth
- Signal and background fit to data

How well can this work?

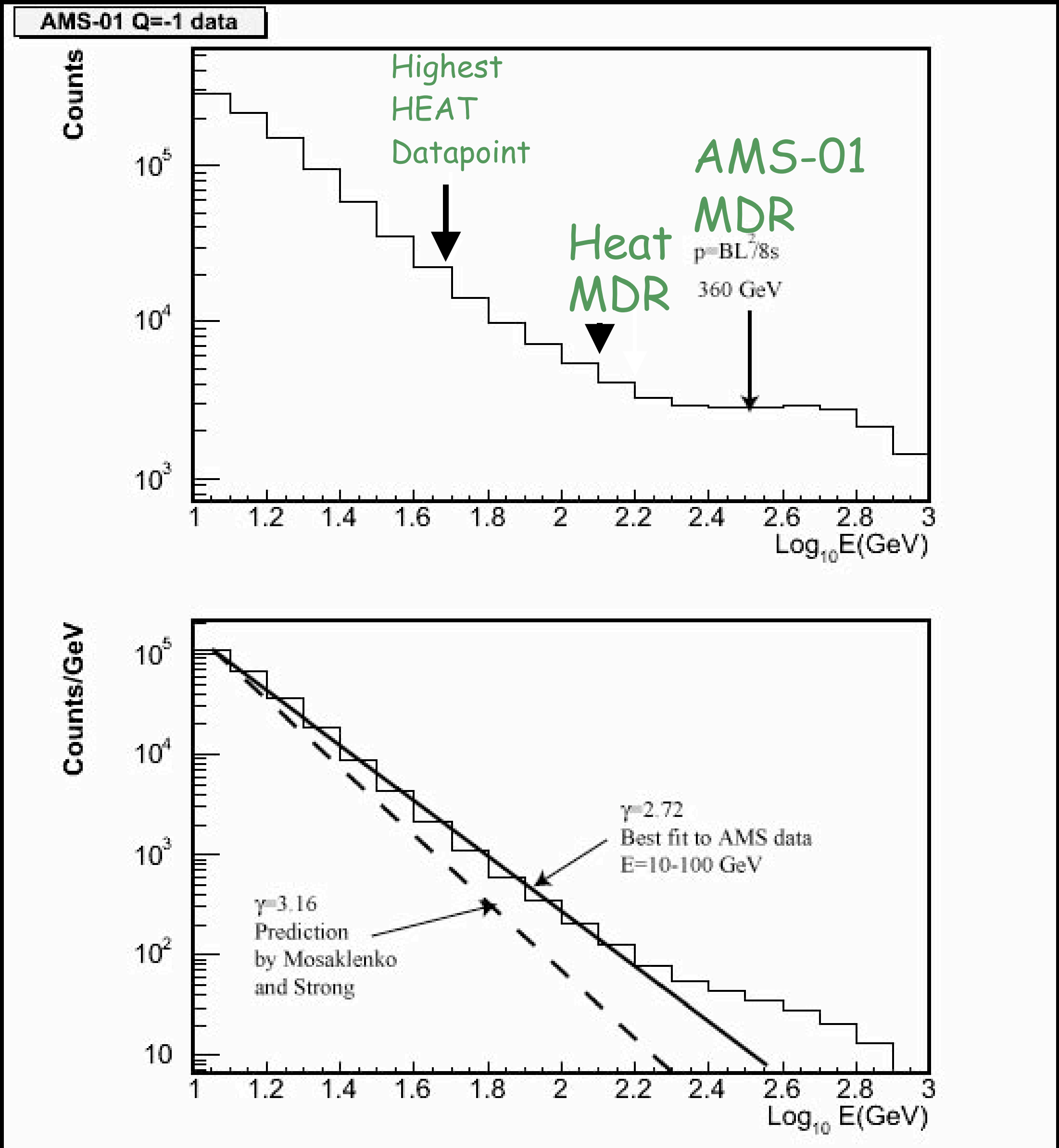
	HEAT	AMS-01	AMS-02
Aperture (m^2-str)	0.05	0.14	0.5
Exposure (h)	45	239	26,000
MDR (GV)	170	360	3,000
FOM for DM e^-	1	0.4-1.5	8-24
Status	Flew	Flew	Mar. 2008 (Hah!)

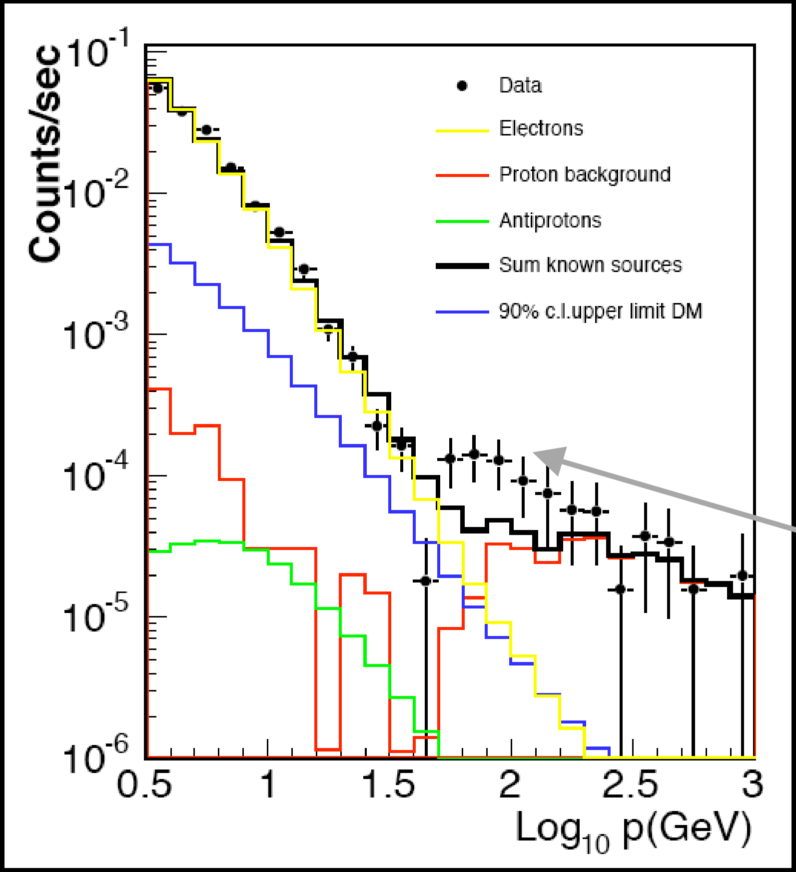
$$FOM = \sqrt{(0.1 \text{ to } 0.01)\frac{\Omega}{0.05\text{m}^2-\text{str}}\frac{\tau}{45\text{h}}}$$

Preliminary AMS-01 Z=-1 selection:

- Downward going
- |Q|=1 from both tracker and TOF
- Well fit track with 4 hits
- Not docked to MIR, not over SAA
- Good match between TOF and track

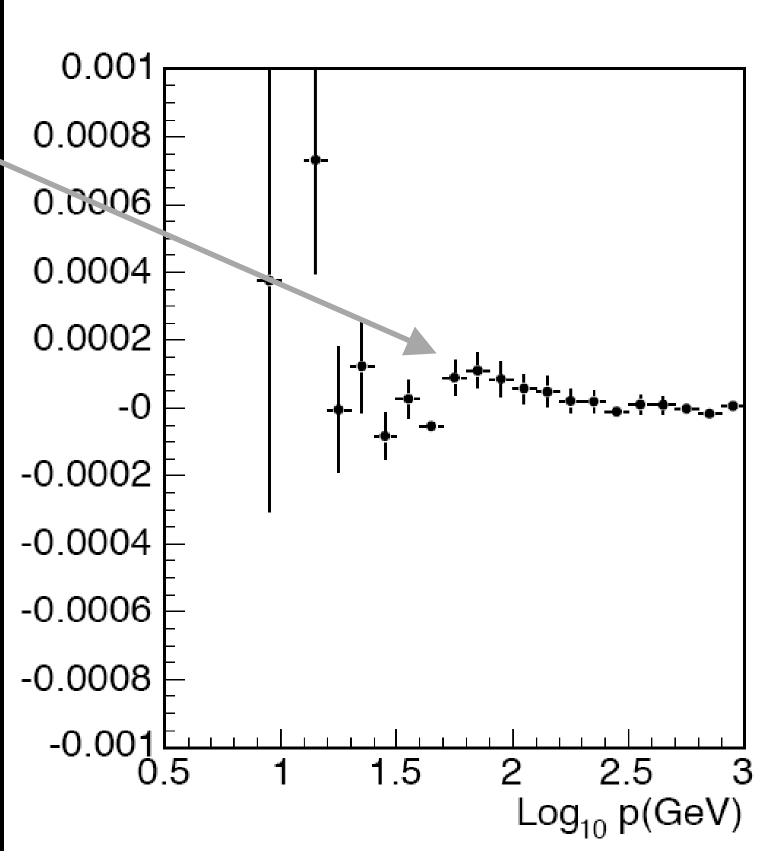
A major difficulty is mis-reconstructed protons in the Z=-1 signal. This background is calculated by Monte Carlo (200 M events)





The primary background is mis-reconstructed protons (shown in red), which dominates for p>50 GeV. Owing to this, the fit is largely determined by the slope at lower energy rather than the spectral cutoff at higher energy.

Trouble here!



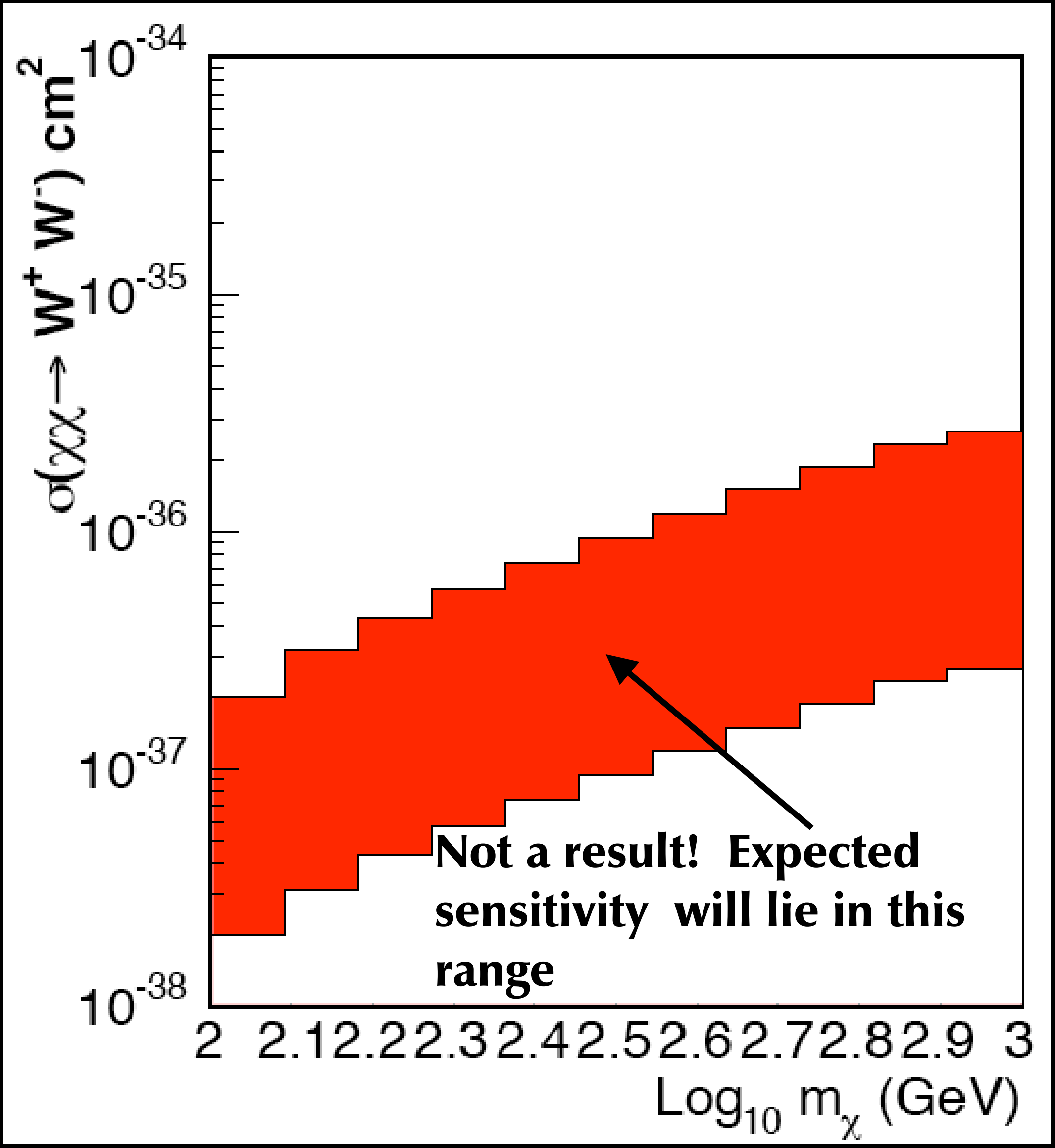
Fit for the normalization of

- Expected electrons
- Expected antiprotons
- DM signal (electrons, antiprotons) from W^+W^- fragmentation

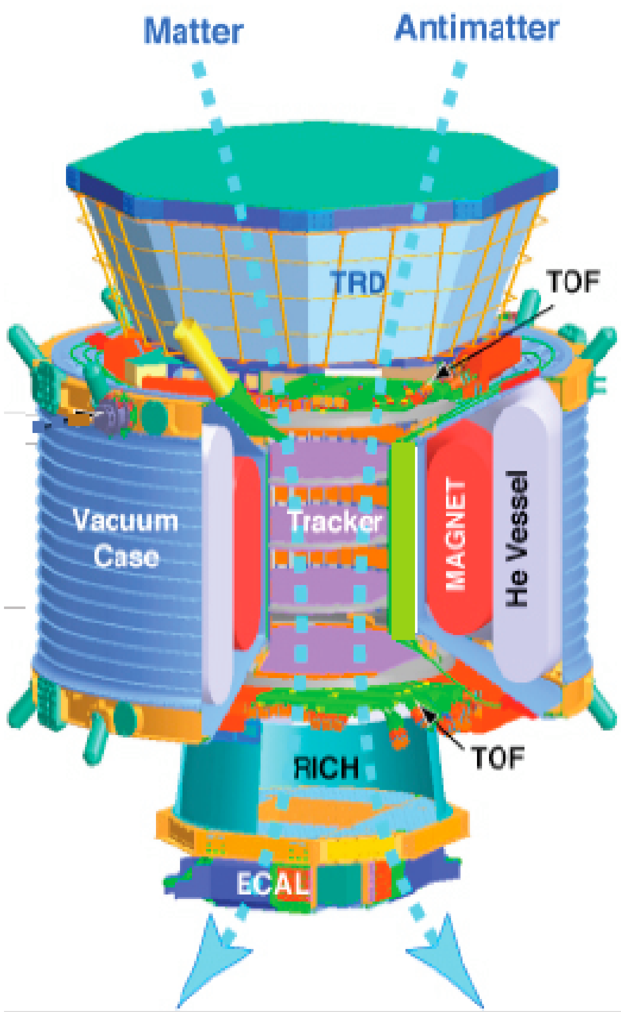
Taking the 90% c.l. upper limit for the DM normalization from the fit gives the exclusion plot shown. The limit is in an interesting region.

Clearly, more work is needed to understand the instrumental effects.

Need something better!

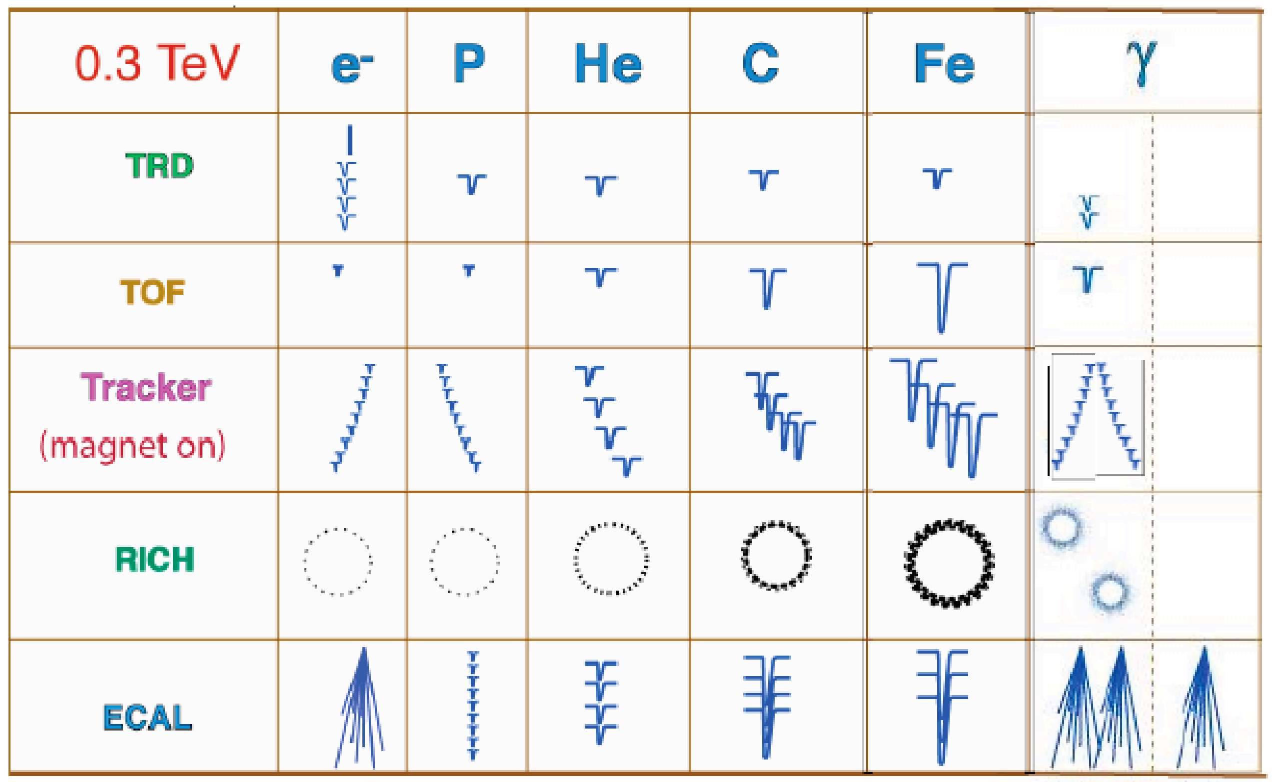


AMS-02



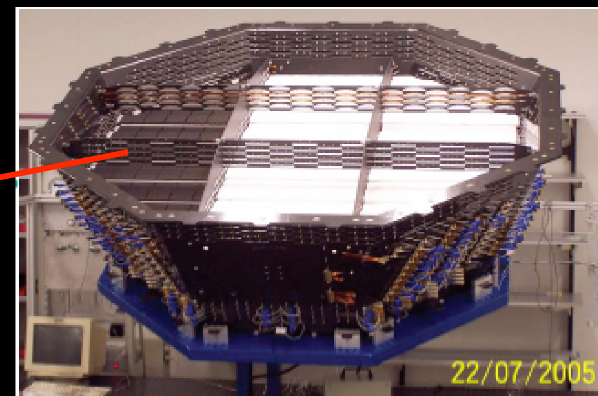
Improvement requires

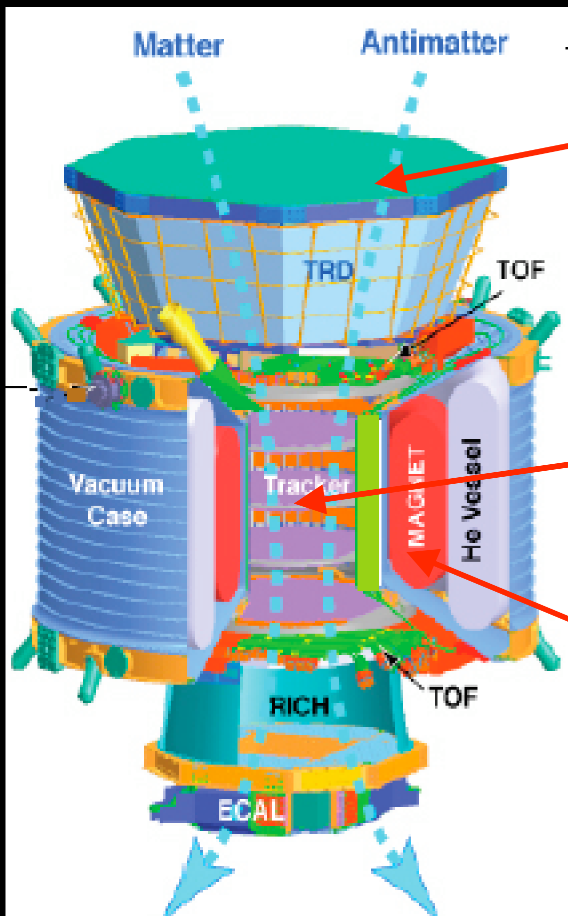
- Much higher statistics - 3 years in orbit, 3x larger aperture
- Higher momentum reach - 7x stronger magnet, two more tracker planes
- Particle ID



See: http://ams.cern.ch

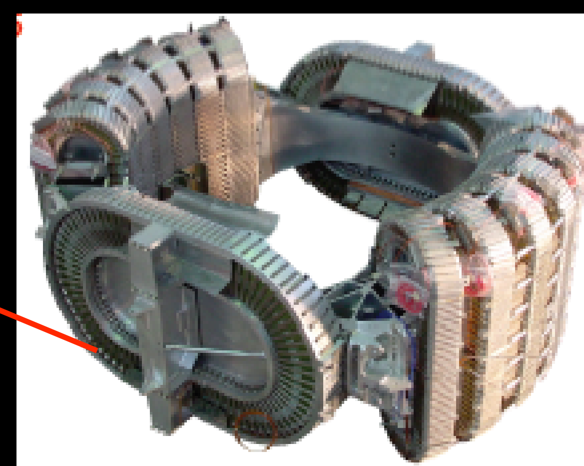
AMS-02 is under construction. All major subsystems are complete or will be complete by Jan. 2006, at which time integration will start.



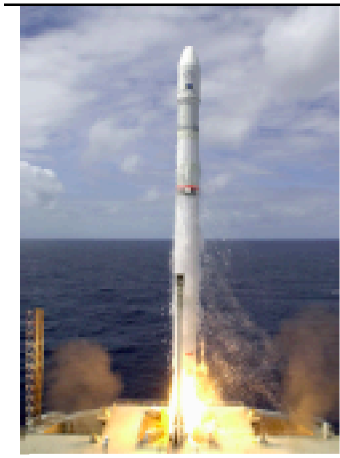


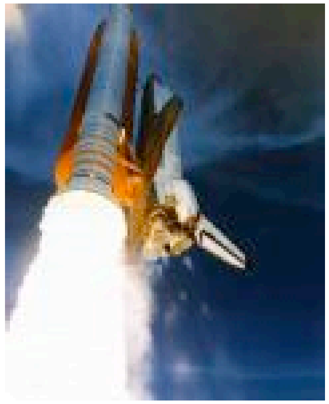
8 plane silicon tracker

20 layer Xe:CO2 transition Radiation Detector



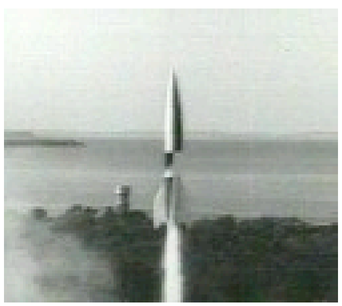
0.7 T superconducting magnet

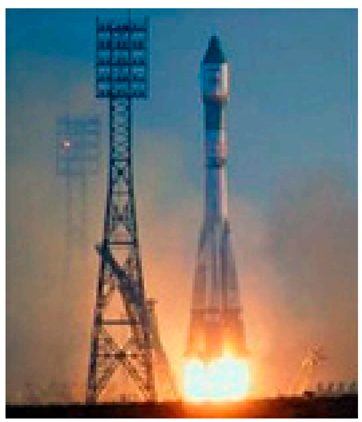




AMS is currently in the NASA manifest for UF-4 which will be in 18 flights. The President's space exploration vision foresees retiring the shuttle in 2010. You do the math…

…all options are being explored.





Summary

- Elucidation of the dark matter problem will eventually require detection or very stringent limits on annihilation in our galaxy
- Detecting the decay products is a tough problem:
    - High statistics requires a large detector (~1 m^2-str), long duration (months)
    - Backgrounds are high
    - Propagation effects are tricky to assess
    - Complex instrument needed for electrons, positrons, protons and anti-protons

For myself, I'm thinking about nuclear recoils